Wednesday, July 29, 1998
ASTEROIDS
8:30 a.m. Walton Theatre

Chairs: C. R. Chapman
J. F. Bell III

Sears D. W. G.*
The Case for Asteroid Sample Return

Wetherill G. W.* Kortenkamp S. J.
Formation of Asteroid Belts Without Runaway Growth of Very Large Planetary Embryos

Kortenkamp S. J.* Wetherill G. W.
Terrestrial Planet and Asteroid Formation in the Presence of Migrating Giant Planets

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Near Earth Asteroid Rendezvous (NEAR) Approaches Eros

Bell J. F. III* Murchie S. Izenberg N. Warren J. Veverka J. Chapman C. McFadden L. Robinson M. Thomas P. Malin M. Clark B. E. Harch A. Farquhar R. Cheng A.
Mineralogy and Composition of 433 Eros from the Near Earth Asteroid Redezvous Mission: Toward a Better Understanding of the Asteroid-Meteorite Connection

Chapman C. R.* Merline W. Thomas P. NEAR MSI-NIS Team
Cratering of the C-type Asteroid Mathilde

Merline W. J.* Chapman C. R. Robinson M. Murchie S. Veverka J. Harch A. Bell J. F. III Thomas P. McFadden L. Malin M. Clark B. E. Izenberg N. Joseph J. Carcich B. Murphy P. Heyler G. Cheng A.
Search for Satellites of 253 Mathilde from Near Earth Asteroid Rendezvous Flyby Data

Benner L. A. M.* Ostro S. J. Rosema K. D. Choate D. Giorgini J. D. Jurgens R. F. Rose R. Slade M. A. Thomas M. L. Winkler R. Yeomans D. K.
Radar Observations of Asteroid 7822 (1991 CS)

THE CASE FOR ASTEROID SAMPLE RETURN. D. W. G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville AR 72701, USA (COSMO@uafsysb.uark.edu).

Over two decades ago the case was successfully made that asteroid sample return was not justified because (a) we had representative samples of asteroids in our laboratories in the form of the meteorites, (b) there was too much uncertainty as to which asteroid should be sampled, (c) the mission was too technically challenging. It is argued that none of these arguments are valid today. There is now a very strong case for asteroid sample return although no clear strategy has been developed. Both asteroid astronomy and meteorite science need such missions.

Notwithstanding more than two decades of research on asteroid spectra and laboratory investigations, the “S asteroid paradox”, the rarity of asteroids with surfaces resembling the most common types of meteorite (Fig. 1), has not been resolved. There is a growing sense that most asteroids come from very few parent bodies and that most asteroids are not providing meteorites. There are many selection effects determining which asteroids produce meteorites and peaks in the cosmic ray exposure age histograms and other data are evidence that most meteorites came from a few parent bodies, *e.g.* the HEDs come from 4 Vesta, and the H chondrites come from 6 Hebe.

We now have a very sophisticated database of spectra for asteroids and the variety and numbers of classes of asteroids is fairly well established (Fig. 1). It is possible to rank asteroids in terms of their abundance in the asteroid belt and potential importance for early solar system studies. Clearly the priority should be to sample a C and an S asteroid for representative material, and a Q asteroid for potential ordinary chondrite material.

The major technical consideration is the energy requirement of the mission. The large energy requirement of main belt missions does not apply to near-Earth asteroids. The energetics for reaching many NEAs are more favorable than for Mars, and several are energetically more favorable than for the Moon. There are NEAs that are C, S , Q and even V (Vesta-like). The number of known NEAs has increased considerably in the last decade or so, and continues to grow, and the distribution of the NEAs over the spectral classes is remarkably similar to that of the main belt (Fig. 1).

The strategy for exploring new worlds has been likened to a geologist exploring a new field. Meteorites are flotsam and what is required now is some knowledge of their likely “outcrops”. Terrestrial geologists first map the field, select representative samples, and perform little or no analysis of the samples in the field but return them to the laboratory for sophisticated analysis. In the case of the asteroids, spectral reflectivity data are equivalent to mapping and sample selection. Asteroid-to-asteroid differences are much larger than differences on an asteroid, so that at this stage only a grab sample is required. Surface samples will be most helpful in understanding the astronomical and meteorite data. Even if the first asteroids sampled are not meteorite parent bodies, the information gained will provide “ground truth” for meteorite studies and new data on primitive solar system materials.

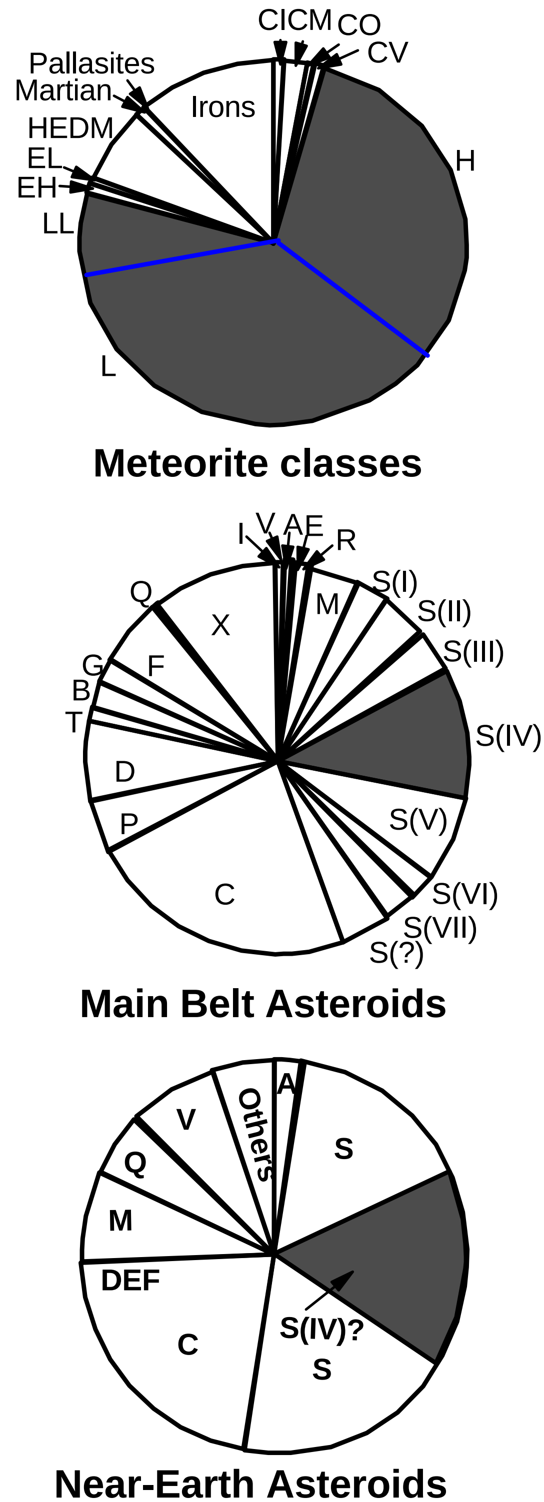

Fig. 1. Distribution of meteorites and asteroids over the classes. The statistics are fairly good for the meteorites and main belt asteroids, but include only ~40 NEAs. The only asteroid match for H, L, and LL chondrites is the Q class and, possibly, the S(IV) class. The distributions for the main belt asteroids and NEAs are remarkably similar.

FORMATION OF ASTEROID BELTS WITHOUT RUNAWAY GROWTH OF VERY LARGE PLANETARY EMBRYOS. G. W. Wetherill[1] and S. J. Kortenkamp, [1]Carnegie Institution of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington DC 20015, USA (wetherill@eros.ciw.edu).

A satisfactory model for the formation of the asteroid belt would be of great help in making use of the exquisite record of early solar system processes preserved in asteroidal meteorites. Any attempt to do so immediately raises the need to explain the absence of planet-sized bodies in that region. Runaway growth of Mars-sized bodies that merged to form the terrestrial planets and the cores of the giant planets is more or less standard belief. But if so, why did this process skip over the asteroid belt? One answer, possibly the best answer, is that runaway growth did occur in that region on a 10^6-year time scale, but a natural process of gravitational clearing has removed these large bodies (Wetherill 1992).

As usual, the above model is not unique and it would be unfortunate if the correct alternative were overlooked by lack of trying. What are the alternatives? Is there a natural process that stops runaways from occurring, and could it have operated in the asteroidal region, but not elsewhere? This is an attempt to begin answering that question.

Runaway growth of planetary embryos from planetesimals is a natural consequence of a system in which the perturbations of the planetesimals are entirely the result of the mutual interactions between the planetesimals themselves (Wetherill and Stewart 1993). The tendency to equipartition of energy between the larger and smaller bodies will reduce the velocities of the larger bodies, increasing the growth rate of the larger bodies, leading to the runaway instability. This suggests that dropping the assumption of dominant mutual perturbations may provide an alternative (Patterson 1989, Wetherill 1989).

It has been shown that long range perturbations by the present giant planets leads to relative velocities between planetesimals in the asteroid belt of several hundred meters/sec, even after taking into consideration the tendency of the perturbed orbits of the planetesimals to remain in phase with one another (Kortenkamp and Wetherill 1998). In the present work, the effect of perturbations of this magnitude on the growth of embryos in the inner solar system has been estimated by including a “background” minimum velocity of 100 m/sec in the calculations of Wetherill and Stewart (1998). After two million years, the largest body had a diameter of only six km. Thus velocities this high seem to preclude not only runaway growth, but any significant growth at all.

It would be excessively speculative to discuss specific smaller but still significant external perturbers in an early Solar System, but an estimate can be made regarding what the magnitude of the background velocity must be to prevent runaway growth. A background velocity of 30 m/sec permits asteroidal bodies (2.5 AU) to grow to 900 km diameter in 5 m.y. whereas at 20 m/sec a body grows to this size in 2 m.y. If such moderate perturbers existed in the early Solar System, “orderly” growth, as described by Safronov (1969), rather than runaway growth could have occurred in the asteroid belt, and the largest bodies that formed there could have been similar in size to those found today. These longer time scales for asteroid growth may also be relevant to the low concentration of radiogenic ^{26}Mg in Al-rich chondrules.

The situation at 1 AU has not been thoroughly studied at this time. It has been shown that for a background velocity of 10 m/sec, a Mercury size embryo can be formed in 200,000 years. It may be that semi-major axis dependent perturbations are required to truncate runaway growth at 2.5 AU, but still permit growth of large embryos at 1 AU.

References: [1] Kortenkamp S. J. and Wetherill G. W. (1998) *LPS XXIX*, abstract #1616-1617. [2] Patterson C. W. (1989) *LPS XX*, 828–829. [3] Safronov V. S. (1969) *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets*., English Transl. NASA TT F-677. [4] Wetherill G.W. and G.R. Stewart (1993), *Icarus*, *106*, 190-209. [5] Wetherill G.W. (1992), *Icarus*, *100*, 307–325. [6] Wetherill G. W. and Stewart G. R. (1993) *LPS XXIII*, 1250–1251.

TERRESTRIAL PLANET AND ASTEROID FORMATION IN THE PRESENCE OF MIGRATING GIANT PLANETS.
Stephen J. Kortenkamp and George W. Wetherill, *Carnegie Institution of Washington - DTM, Washington, DC, 20015, kortenka@dtm.ciw.edu*.

Conventional theories put forth to explain terrestrial planet formation surmise that small micrometer-sized grains in the early solar nebula coagulated into larger particles. These macroscopic particles further accumulated into aggregates in the size-range of hundreds of meters to a few kilometers -- the planetesimals. These planetesimals are largely decoupled from the gaseous nebula and orbit the Sun with Keplerian motion, leading to a small relative velocity with respect to the partially pressure-supported nebula. The resulting gas drag dissipates energy and angular momentum, circularizing the planetesimal orbits and reducing their mutual inclinations while slowly causing them to decay towards the Sun. By this process the planetesimals evolve on very nearly circular co-planar orbits perturbed only by their mutual gravitational interactions. Relative encounter velocities for bodies on such orbits are ~ 10 cm s^{-1}. Given these conditions run-away growth of lunar- to mars-sized planetary embryos occurs, with one such embryo in each accretion zone of width ~ 0.05 AU (Wetherill & Stewart 1993). Models pertaining to the final stages of terrestrial planet formation typically evolve these planetesimals and embryos for 5 to 10 million years before introducing Jupiter and Saturn and dissipating the gaseous nebula. By this scenario numerous model planetary systems have been produced that are not altogether too remarkably different from the terrestrial planets of our Solar System (Wetherill 1996; Chambers and Wetherill 1998).

Recent discoveries of extra-solar giant planets and the refined interior models of Jupiter and Saturn (Chabrier *et al.* 1992; Guillot *et al.* 1994) have spurned a revival of the gravitational instability theory for giant planet formation. This theory postulates that gravitational instabilities in the gaseous solar nebula lead to clumping of the nebula and eventual collapse of fragments into giant gaseous protoplanets (GGPPs) which presumably then evolve into giant planets like Jupiter and Saturn. Boss (1996) has shown that low mass protoplanetary disks accreting material from a spherical halo have hot inner disk temperatures (~ 1200 K inside of 4 to 5 AU) and cool outer disk temperatures (~ 100 K outside of 4 to 5 AU). He later showed (Boss 1997) that under these conditions the outer disk is unstable towards GGPP formation. Boss (1998) has since shown that in an intermediate mass disk ($\sim 0.14\ M_\odot$ inside 10 AU), as a single GGPP forms near 6 AU, if the location of the center of mass of the protostar/disk system is preserved (ie., if the protostar is allowed to wobble as the first GGPP forms) then a second GGPP will be triggered near 10 AU, with both GGPPs forming in less than 10^3 years.

Boss's disk models have led him to entertain the notion of a ''best of both worlds'' scenario for planet formation, whereby Jupiter and Saturn formed from GGPPs in the cool outer disk while the terrestrial planets formed in the hot inner disk by collisional accumulation of small planetesimals. If this was the case then the formation of terrestrial planets and gas giants, which have traditionally been modeled as separate processes, may have occured simultaneously and thus affected each other.

The distribution of encounter velocities is one of the key factors which controls the rate of planetesimal growth. In this regard the gravitational influence of giant planets is important because of the smooth secular perturbations which act on orbits at all semi-major axes. For a given planetesimal density the orbits of smaller bodies decay faster than those of larger bodies. When a range of planetesimal sizes was studied (Kortenkamp & Wetherill 1998) we found that as the orbits of smaller bodies decay past the orbits of larger bodies the orbits of the two sets are not in phase, that is, they do not evolve on coplanar concentric orbits. Small planetesimals in the range of 0.1 to 1 km radius had encounter velocities of $\gtrsim$100 m s^{-1} near 2.5 AU and 20 to 40 m s^{-1} near 1 AU. Such high encounter velocities may prevent the formation of asteroids (near 2.5 AU) greater than six km diameter (Wetherill & Kortenkamp 1998).

In our previous models we began, at time $t = 0$, with Jupiter and Saturn at their present masses and in their present orbits. However, recent work by Trilling *et al.* (1998) has shown that giant planets may undergo substantial inward radial migrations caused by torques between the planets and the solar nebula. In the present work we will report on our efforts to account for the possible migration of Jupiter and Saturn by initially placing them at larger semi-major axes than they currently have.

Boss 1996. Evolution of the solar nebula III: Protoplanetary disks undergoing mass accretion. *Astroph. J.* **469**, 906--920.

Boss 1997. Giant planet formation by gravitational instability. *Science* **276**, 1836--1839.

Boss 1998. Giant planet formation and wobbling protostars. *Lunar Planet. Sci. Conf.* **29**, (abstract on CD).

Chabrier *et al.* 1992. The molecular-metallic transition of hydrogen and the structure of Jupiter and Saturn. *Astroph. J.* **391**, 817--826.

Guillot, T. *et al.* 1994. Nonadiabatic models of Jupiter and Saturn. *Icarus* **112**, 354--367.

Kortenkamp & Wetherill 1998. Terrestrial planet and asteroid formation in the presence of giant planets. *Lunar Planet. Sci. Conf.* **29**, (abstract on CD).

Wetherill 1996. The formation and habitability of extrasolar planet. *Icarus* **119**, 219--238.

Wetherill & Stewart 1993. Formation of planetary embryos: Effects of fragmentation, low relative velocity, and independent variation of eccentricity and inclination. *Icarus* **106**, 190--209.

Wetherill & Kortenkamp 1998. This meeting

FACTORS CONTROLLING THE BULK DENSITIES OF ASTEROIDS. Lionel Wilson[1,2], Klaus Keil[1] and Stanley G. Love[3] [1]HIGP/SOEST, University of Hawai'i, Honolulu HI 96822, USA; [2]IENS, Lancaster University, Lancaster LA1 4YQ, UK; [3]Jet Propulsion Laboratory, Pasadena CA 91109 USA (keil@pgd.hawaii.edu)

Introduction: The bulk densities which have been measured or inferred for the C-type asteroidal bodies 253 Mathilde [1], Phobos [2] and Deimos [3] lie in the range 1300 to 2200 kg m^{-3}. Spectroscopic evidence [1] relates these asteroids to CM chondrite meteorites which have densities of order 2100 kg m^{-3} [4]. Thus, despite the large errors associated with the asteroid density measurements (commonly up to 25%), these data imply that some asteroids have bulk porosities of order 30-40%. This is in marked contrast to the porosities of the apparently related meteorites, which are of order 15 percent [4]. We consider two processes which may have led to the low bulk densities of asteroids.

1) Low-velocity impact disruption: Melosh and Ryan [5] have recently shown that, for all asteroids larger than about 400 m in radius, the impact energy needed to disperse an asteroid is greater than the energy required to extensively shatter it. Thus the vast majority of present-day asteroids are probably gravitationally bound but strengthless rubble piles. We have modelled the motions under their mutual gravitational attractions of the fragments generated during typical fragmentation and re-accretion events using suitably scaled data on fragment size and velocity distributions [6]. We find that, because the sizes and velocities are systematically coupled (small fragments being ejected at the highest speeds), the largest fragments will re-accrete before the smaller fragments. The irregular shapes of these objects will ensure that relatively large spaces are left between them, the low velocities of re-accretion leading to little crushing of the fragments. The early-arriving fragments will be coated with a layer of later-arriving, smaller fragments which will to some extent fill in the gaps, but our simulations suggest that substantial internal porosity will be preserved by this process. This process is expected to operate to some extent in all asteroids, irrespective of composition.

2) Gas loss during aqueous alteration: We have investigated the physical consequences of aqueous alteration during the early histories of chondritic meteorite parent asteroids [7]. We find that substantial gas pressures may have evolved on time scales of up to 0.1 Ma, despite gas loss due to the finite permeability of these bodies. These pressure may have eventually exceeded the tensile strength of the parent body leading to fracture formation and gas loss. Fracture initiation will have been aided by impact events. The energetics of gas expansion and consequent entrainment and acceleration of small fragments are such that, for asteroids up to a few tens of km in radius, a significant fraction of the interior volume of the asteroid may have been discharged into space at escape velocity. Despite some readjustment of the residual material, this process could also have lead to substantial residual bulk porosity. The relative importance of these two processes is the subject of continuing study.

References: [1] J. Veverka et al. (1997) Science 278, 2109. [2] D.E. Smith et al. (1995) GRL 22, 2171. [3] P. Thomas et al. (1992) in Mars (U. of Arizona Press) p. 1257. [4] Consolmagno et al. (1997) M&PS 32, #4 (Suppl), A31. [5] Melosh, H.J. and Ryan, E.V. (1997) Icarus 129, 562. [6] A. Nakamura and A. Fujiwara (1991) Icarus 92, 132. [7] L. Wilson et al. (1997) LPSC 29, #1275,

NEAR EARTH ASTEROID RENDEZVOUS (NEAR) APPROACHES EROS. M. S. Robinson[1], A. Harch[2], S. Murchie[3], J. Veverka[2], J. F. Bell III[2], C. Chapman[4], L. McFadden[5], M. Malin[6], P. Thomas[2], E. Hawkins[3], R. Farquhar[3], and A. Cheng[3], [1]Northwestern University, Evanston IL 60208, USA, [2]Cornell University, Ithaca NY 14853, USA, [3]Applied Physics Lab, Johns Hopkins University, Laurel MD 20723, USA, [4]Southwest Research Institute, Boulder CO 80302, USA, [5]University of Maryland, College Park MD 20742, USA, [6]Malin Space Science Systems, San Diego CA 92191, USA.

The Near Earth Asteroid Rendezvous (NEAR) spacecraft was launched on February 17, 1996, toward a rendezvous, scheduled for January of 1999, with the asteroid 433 Eros [1]. Eros is the second largest (~20 km diameter) Near Earth Asteroid and it comes within 0.15 AU of the Earth at closest approach. It is an S-Type asteroid that exhibits color heterogeneity in Earth-based spectra interpreted to indicate compositional heterogeneity at the hemisphere scale [2].

NEAR successfully encountered the asteroid 253 Mathilde on June 27, 1997, and returned the first ever resolved image data of a C-type asteroid [3]. The Mathilde flyby trajectory brought NEAR within a range of ~1200 km and a relative velocity of ~10 km/second [3,4]. Science highlights of the encounter include the discovery that Mathilde's density is 1.3±0.3 g/cm^3 [5] and that it is host to at least five well-preserved craters with diameters of 19–33 km (the mean radius of Mathilde is only 26.5±1.3 km [3]).

The NEAR spacecraft made a close approach to the Earth on January 23 of this year for a gravity assist to adjust the spacecraft's heliocentric orbit energy and orbital inclination to match that of Eros [6]. At this time calibration data were acquired for all science instruments utilizing both the Earth and/or the Moon as targets.

The first attempt to image 433 Eros will occur in August of this year on the 100th anniversary of its discovery by G. Witt and A. Charlois. However, 433 Eros will not be resolved with the imager until December, and orbital insertion will begin on January 10, 1999. Once in orbit NEAR will map the asteroid with its complement of six science instruments (Gamma-Ray Spectrometer - XRS; Magnetometer - MAG; Multi-Spectral Imager - MSI; Near-Infrared Spectrometer - NIS; Near Laser Ranger - NLR; X-Ray Spectrometer- XRS). Additionally, radio science will be performed with the spacecraft X-band transponder [1,4].

The main science goals of the mission are: (1) to characterize the asteroid's physical and geologic properties, (2) to infer its elemental and mineralogic composition, (3) to clarify the relationships between asteroids, comets and meteorites, and (4) to advance the understanding of processes and conditions during the formation and early evolution of planets. Key measurements to meet these science goals include size, shape, mass, density, gravity field, spin state, elemental and mineralogic composition of the surface, morphology and texture, and magnetic properties [6]. These measurments will be carried out in orbit around Eros over the course of a little over one Earth year. During much of the mapping phase the spacecraft's orbit will have a periapse of 35 km or lower, during which it will be possible to image much of Eros' surface at better than 2 m/pixel.

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MINERALOGY AND COMPOSITION OF 433 EROS FROM NEAR: TOWARDS A BETTER UNDERSTANDING OF THE ASTEROID-METEORITE CONNECTION.

J. F. Bell III[1], S. Murchie[2], N. Izenberg[2], J. Warren[2], J. Veverka[1], C. Chapman[3], L. McFadden[4], M. Robinson[5], P. Thomas[2], M. Malin[6], B.E. Clark[2], A. Harch[2], R. Farquhar[2], A. Cheng[2], [1]Cornell University, Ithaca NY 14853, [2]Applied Physics Lab, Johns Hopkins University, Laurel MD 20723, [3]Southwest Research Institute, Boulder CO 80302, [4]University of Maryland, College Park MD 20742, [5]Northwestern University, Evanston IL 60208, [6]Malin Space Science Systems, San Diego CA 92191.

Introduction. The Near Earth Asteroid Rendezvous (NEAR) mission will begin systematic exploration and mapping of the asteroid 433 Eros in early 1999 [1]. The primary goals of the NEAR mission are to determine Eros' size, shape, volume, density, and spin state, to characterize the geology and morphology of the surface at high spatial resolution, to infer regolith and textural properties of the surface, and to measure the elemental and mineralogical composition of the asteroid with sufficient accuracy to enable comparisons with major meteorite types. To achieve the latter goal, NEAR is equipped with a multispectral imager (MSI) for visible to near-IR color observations [2], a near-IR spectrometer (NIS) for higher spectral resolution mineralogic mapping [2,3], and an X-ray/Gamma-ray spectrometer (XGRS) for elemental compositional mapping [4]. These instruments are complementary to each other and will generate data that will address fundamental questions in asteroid and meteorite science. This presentation focuses primarily on NIS, including its instrumental characteristics, initial calibration results, observation strategy, and expected data products.

The Asteroid-Meteorite Connection. Near-IR spectroscopy has been the primary technique used to identify the mineralogy of asteroid surfaces [5]. Classifications [6] based on colorimetric properties, refined using information on the chemistry and mineralogy of Fe, Mg, Ca-bearing surface materials (e.g., olivine, pyroxene, spinel, metal), have revealed important differences among the asteroids, related to varying conditions of formation and/or subsequent modification. Eros has been classified as an S type, and groundbased spectroscopic measurements have shown it to have both olivine and pyroxene heterogeneously distributed on its surface [7]. Much controversy exists about the relationship between the S type asteroids (the most common asteroid class), and the most common class of meteorites, the ordinary chondrites. Are the S types also undifferentiated and are they the source of these meteorites? Or are they the differentiated parent bodies of some of the stony-iron and achondrite meteorites? Is there some "space weathering" process [8] that complicates the identification of a link between the asteroids and meteorites? Is the diversity of S asteroid compositions [9] evidence for multiple sources (of both the asteroids and the chondritic meteorites)? Using NEAR data, we hope to provide answers to these and other questions related to the asteroid-meteorite link.

NIS Operation and Observations. NIS is a grating spectrometer that uses 64 detectors to measure the spectrum of sunlight reflected off Eros in the 800 to 2600 nm wavelength region. The spectral resolution is 22 nm from 800 to 1500 nm, and 44 nm from 1500 to 2600 nm. Observations will be conducted at each stage of the mission as the orbital radius is lowered from several hundred km down to 35 km (Eros is ~ $40 \times 14 \times 14$ km diameter). The instrument has narrow and wide fields of view (6.5×13.0 mrad and 13.0×13.0 mrad), yielding spatial resolution as good as 100×200 m from an altitude of 15 km above the surface. NIS has a scan mirror to allow off-nadir measurements of surface features at low phase angles (including 0°), and for generating image cube mosaics of the asteroid in 64 channels. Nominal NIS operations will involve close collaboration with MSI and XGRS to generate high spatial resolution morphology, moderate spatial resolution mineralogy, and low spatial resolution elemental chemistry maps of the entire asteroid surface.

Initial Instrument Performance and Expected Data Quality. NIS carries an onboard diffuse gold calibration target that is used to verify and monitor the radiometric calibration of the instrument. Inflight tests during the first two years after launch verified the stability of the radiometry and the low level of instrument and spacecraft background noise. During the NEAR Earth swingby of January 23–26, 1998, NIS obtained high-quality spectra of the Earth and Moon as its first test on real geologic targets. The data are being used to refine the NIS instrumental calibration prior to Eros operations, and they reveal that the instrument should obtain spectra with instrumental SNR in excess of 200–300 at wavelengths below 1500 nm and between 50–100 for most wavelengths longward of 1500 nm.

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CRATERING OF THE C-TYPE ASTEROID MATHILDE. Clark R. Chapman[1], William Merline[1], Peter Thomas[2], and the NEAR MSI-NIS Team, [1]Southwest Research Inst., #426, 1050 Walnut St., Boulder CO 80302, USA (cchapman@boulder.swri.edu), [2]CRSR, Cornell Univ., Ithaca, NY 14853, USA.

The 53 km diameter C-type main-belt asteroid 253 Mathilde was imaged by the Near Earth Asteroid Rendezvous (NEAR) spacecraft on 27 June 1997 [1]. Not only is Mathilde's surface covered with craters, but several giant craters (4 with diameters larger than the radius of Mathilde itself) dominate the shape of the asteroid. Nearly 300 smaller craters were identified on the portions of Mathilde studied (regions totalling 1155 sq. km. with good lighting and viewing geometry, avoiding the often-shadowed interiors of the giant craters). Craters 0.5 to 5 km diameter approach saturation equilibrium spatial densities, with a differential power-law slope of -3; they exhibit a range of degradation states, similar to crater populations on Ida. They probably represent a population in quasi-equilibrium between creation and destruction of craters caused by saturation cratering of Mathilde.

The giant craters are a major surprise. It had been thought that an object's radius was roughly the limit for size of crater that could be produced on it without substantially disrupting the body, at least to the point of "resetting" the surface topography. Yet one crater is 30% larger than Mathilde's radius and three others exceed a radius. The large craters alone (on the 58% of Mathilde that is represented) exceed the usual definition of geometric saturation. Since only one of these craters can have resulted from the latest large impact, the fact that the others exist -- generally with fairly pristine morphology -- means that these impacts were unexpectedly ineffective in destroying pre-existing topography.

The composition and internal structure of Mathilde may contribute to the unusual retention of giant craters. The bulk density of Mathilde [1,2] is very low, about 1.3 gm/cm^3. Even assuming that Mathilde is made of the least dense known meteoritical materials (carbonaceous chondritic, which seems likely from its C-type reflectance spectrum), there must be additional porosity. One possibility is that Mathilde is a rubble pile, with large internal voids. Another is that Mathilde is composed of material even more porous (on a fine scale) and less dense than carbonaceous chondrites. We must remember that the Earth's atmosphere biases meteorite collections toward unusually strong examples of carbonaceous meteorites. Whatever the nature of Mathilde's porosity, it must damp the propagation of shock waves through the interior of the body and may also dramatically reduce ejecta velocities, thereby confining and limiting the damage done exterior to a crater's periphery. This style of cratering has never been recorded on any other solar system body, but it could be typical for primitive asteroids and comets, of which Mathilde is the first to be closely studied.

Calculation of an "age" for Mathilde is highly model-dependent, but it is plausible that Mathilde is billions of years old. There is no reason to require, however, that the giant craters are due to some ancient, now vanished, population of projectiles. Allowing for statistics of small numbers, they are compatible with the size distribution of modern-day projectiles in the inner solar system. We will speculate on possible implications from this first reconnaissance of a C-type asteroid for the derivation of C-type meteorites from the asteroid belt.

References: [1] Veverka J. et al. (1997) *Science, 278*, 2109-2114. [2] Yeomans D. et al. (1997) *Science, 278*, 2106-2109.

SEARCH FOR SATELLITES OF 253 MATHILDE FROM NEAR FLYBY DATA. W. J. Merline[1], C. R. Chapman[1], M. Robinson[2], S. Murchie[3], J. Veverka[4], A. Harch[4], J. Bell III[4], P. Thomas[4], L. McFadden[5], M. Malin[6], B. E. Clark[4], N. Izenberg[3], J. Joseph[4], B. Carcich[4], P. Murphy[3], G. Heyler[3], A. Cheng[3]. [1]Southwest Research Institute, Boulder, CO (merline@boulder.swri.edu), [2]Northwestern University, [3]Johns Hopkins University, Applied Physics Laboratory, [4]Center for Radiophysics and Space Research, Cornell University, [5]University of Maryland, Department of Astronomy, [6]Malin Space Science Systems, Inc.

On June 27, 1997 the NEAR spacecraft,on its way to a one-year orbital mission at the near-Earth asteroid 433 Eros, flew past 253 Mathilde, a C-type, inner-Main-Belt asteroid. Preliminary science results can be found in Veverka, et al.[1]. One of the major science goals was to perform a search for satellites, in part motivated by curiosity about the asteroid's extraordinarily slow rotation rate and speculations that a large satellite may be the explanation. We obtained 534 images of the asteroid and its environs, with over 200 pictures devoted specifically to a search for satellites. As yet, we have found no unambiguous evidence for satellites.

NEAR's Mathilde imaging strategy was restricted by the lack of scan platform for the camera and the requirement to keep the solar panels pointed toward the Sun, within certain limits. Because of these restrictions and the high phase angle, approach imaging was not favorable for the search. Most of the search images were acquired while outbound from the asteroid at phase angles of about 40 degrees. From these images, we were able to search 4% of the Hill sphere (here assumed to have a radius 100 times that of the asteroid) down to limiting visual magnitude of about 10.5, which translates into a size limit of as small as 40 m diameter. From approach images, we were able to search the entire Hill sphere. We found no satellites larger than 10 km diameter in the full Hill sphere and therefore nothing large enough to account for Mathilde's low spin rate.

The longest exposures (1 sec in a clear filter) were the most useful in the search itself. However, these images were interspersed with images in other filters and shorter exposures so that any detections of a satellite could be compared directly with Mathilde and we would have undersaturated, color images of any resolved satellites. Images were taken in several sequences, out to a range of about 12,000 km from Mathilde at 1200 sec past closest approach. Within the sequences, images are generally taken at intervals of two seconds.

Our initial search strategy was to visually inspect the individual images and movie sequences for the presence of persistent objects". Contributing to the confusion were cosmic ray hits, background stars, and detector defects. In addition, a portion of each pixel is a dead-zone, and therefore the counts in a star image may fluctuate from one image to the next; for faint signals, the image may come and go between frames. With the large number of images, cosmic rays could normally be eliminated because of their lack of persistence. When sequences of cosmic rays conspired in successive frames to mimic a moving (by change in perspective) satellite, one could often eliminate the ossibility by looking for consistent brightness between frames. Templates of the ackground sky were used to eliminate stars down to about 10th magnitude. Each image of size 2.25 x 2.9 degrees) contained about 25 background stars.

Our lower-limit search volume only extends out to about 20 asteroid radii, while the present-day synchronous orbit is at about 27 radii. Thus, an object in synchronous orbit, but below 10 km in size, could still be present.

The possibility of satellites around asteroids has long been the subject of scientific debate. Despite numerous observational hints that some asteoids have satellites, there is definitive evidence of only one such system, Ida and its satellite Dactyl, discovered by the Galileo flyby in 1993. Recent theoretical and computational work, however, suggests that asteroidal satellites may be common.

Although the finding that Mathilde lacks a significant satellite is preliminary, it is significant. Future work on the data will push down the limiting size somewhat, refine the volume of space surveyed, and possibly even reveal one or more small satellites near the threshold. Nevertheless, we can speculate on the implications of the negative finding.

Considerations of the origin of Dactyl (Durda[2], Davis, et al.[3]) generally invoke retention of fragments in a catastrophically disruptive collision, of the sort that would be expected to form an asteroid family. Indeed, Ida is a member of the Koronis family. Gaspra, which lacks a satellite, has been less confidently assigned to the Ariadne (or Flora) family (Zappala, et al.[4]). According to Zappala, et al.[4] (and others), Mathilde is not a family member. Perhaps it lacks a satellite in part because it is a battered but nonetheless intact original accretion. Alternatively, Mathilde may once have been a product of a catastrophic collision, but that may have been so long ago that the family has since dispersed. Although processes of family dispersal are not well understood, it is clear from the density of large craters on Mathilde that it must be relatively old. It could well be that Mathilde once had a satellite but, because so much time has elapsed, the satellite has since been destroyed. If so, our data also indicate a lack of debris larger than 40 m within the synchronous orbit.

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RADAR OBSERVATIONS OF ASTEROID 7822 (1991 CS). L. A. M. Benner, S. J. Ostro, K. D. Rosema, D. Choate, J. D. Giorgini, R. F. Jurgens, R. Rose, M. A. Slade, M. L. Thomas, R. Winkler, D. K. Yeomans, *Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA, 91109-8099, USA, lance@echo.jpl.nasa.gov.*

We report Doppler-only (cw) radar observations of 1991 CS obtained at Goldstone at a transmitter frequency of 8510 MHz (3.5 cm) on 1996 August 26, 27, 28 and 29. Weighted, optimally filtered sums of cw echoes achieve signal-to-noise ratios in excess of 300 per day that thoroughly cover the asteroid in rotation phase (synodic period = 2.39 h, obtained photometrically by [1]). A weighted sum of all cw spectra gives an OC radar cross section of 0.24 ± 0.08 km^2 and a circular polarization ratio of 0.28 ± 0.003. Our observations place up to fifty 0.98-Hz resolution cells on 1991 CS at echo powers greater than two standard deviations of the noise. Variations of $\sim$10 Hz in the echo's 2-sigma bandwidth are evident on each day and are consistent with the rotation period. Inversion of echo edge frequencies yields convex hulls of the pole-on silhouette for each day. The hulls have a mean elongation and rms dispersion of 1.18 ± 0.02 and place a lower bound on the maximum pole-on dimension of 1.3 km/$\cos\delta$, where δ is the angle between the radar line-of-sight and the asteroid's pole direction (which is unknown). The hulls suggest that 1991 CS has the least elongated pole-on silhouette of any near-Earth asteroid for which similar shape information is available. If we assume that the projected area of 1991 CS is the same as that of a sphere with a diameter of 1.1 km, equal to the lower bound on the minimum breadth of the pole-on silhouette on August 28 and 29, then 1991 CS' radar cross section and absolute magnitude of 17.5 [1] correspond to upper limits on the radar and optical geometric albedos of 0.25 and 0.14 that are consistent with its S-class taxonomy [2,3]. Among the nineteen S-class asteroid radar detections previously reported [4-8], the circular polarization ratio of 1991 CS is greater than eleven, comparable to three, and less than five [4-8].

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